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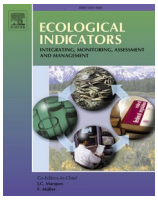

Indicators of body size variability in a highly developed small-scale fishery: Ecological and management implications

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ABSTRACT

Body size plays a key role for the productivity and resilience of marine populations. This work analyses the variation in body size indicators taken from ~ 400 000 individuals during the period 2000–2018 for a set of 20 key commercial species of the small-scale fishery of Galicia (SW Europe). Mean body size showed relatively stable inter-annual trends during the study period, and, at the year level, mean body size for most species followed seasonal cycles. Body size was negatively related to the number of individuals caught per haul. Bathymetry also explained part of the variation in individual body size with species-specific depth affinities. Common trends in the species' body size showed an increasing trend in the northern region while decreasing in the south suggesting differences in local environmental conditions and/or in the dynamics of the fishery. The skewness of body size distributions varied slightly from year to year, although some species showed significant trends. The annual trend of the species-specific skewness was negatively related to the proportion of immature individuals in the catch and positively related to the rate of change in abundance, suggesting a reduction of recruitment success in response to differences in size-selective exploitation patterns probably ascribed to minimum landing size being generally below size at maturity. The combination of body size and abundance indicators revealed a relatively stable performance of some of the most important resources targeted by the Galician small-scale fishery sector during the last two decades. However, our study highlights also the need to align management measures with biological reference points in order to prevent long-term reductions in stock productivity.

1. Introduction

Body size plays a key role for the productivity and resilience of marine populations and affects many other life history traits. For instance, the stock's reproductive potential is not proportional to female body size as big, old and highly fecund females have a higher weight-specific reproductive output within a population (Barneche et al., 2018; Birkeland and Dayton, 2005; Hixon et al., 2014; Kjesbu et al., 1996). However, body size not only affects fecundity and offspring size and quality, but also reproductive timing (Wright and Trippel, 2009), sex change (Hamilton et al., 2007) or even fish behaviour (Villegas-Ríos et al., 2013). Therefore, changes in body size have broad implications for the fate and resilience of fish populations, stock dynamics and the overall structure of ecosystems (Andersen et al., 2019).

The size structure of populations is in turn affected by multiple factors including environmental conditions, changes in stock size, ecological interactions and anthropogenic disturbances, such as fishing pressure that influences individual growth and size-dependent mortality (Rogers et al., 2011; Swain et al., 2007). In many cases, body size measurements are the unique source of demographic information from a fishery. Accordingly, size-based indicators, such as mean length of a stock, have been traditionally used to study the response of populations to exploitation (Beverton and Holt, 1956). Decreasing body size is generally associated to deleterious trends of the status of the population. Life-history theory predicts that increased fishing mortality generally leads to reduced average age of the fish in an exploited population (Beverton and Holt, 1956; Ottersen, 2008), promoting population instability and resulting in an increase in the sensitivity of the species to the environmental conditions and natural selection pressures (Audzijonyte et al., 2013; Barnett et al., 2017; Planque et al., 2010). Moreover, size-dependent mortality can cause further genetic changes of fish life histories, i.e. lower growth rates (Uusi-Heikkilä et al., 2015). Additionally, environmental variability can also drive changes in size composition (Baudron et al., 2014; Genner et al., 2010) as a

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physiological response to increases in the temperature of aquatic ecosystems (Daufresne et al., 2009). However, disentangling the main forcing factors of current body size trends in harvested populations is difficult but of capital relevance to evaluate past and current stock performance and predict future scenarios.

It is widely recognized that small-scale fisheries (SSFs) play a major role in worldwide fish catches and food supplies and security (Chuenpagdee and Pauly, 2008; Weeratunge et al., 2014). However, the lack of attention that these fleets have experienced historically is reflected in the lack of formal assessments, which is a main concern given that poorly understood fisheries seem to be in substantially worse condition than the well-studied ones (Costello et al., 2012). Within this context, length frequency data of the catch is probably the most common source of demographic information because body size data are routinely collected in a cost-effective manner in many data-limited situations. Indeed, time-series of size-based indicators (SBI) are used to trace demographic changes in marine populations and communities and study their potential causes (Ohlberger et al., 2018; Rypel et al., 2016; Shin et al., 2005). For instance, mean length of the catch is inversely correlated with fishing mortality (Beverton and Holt, 1956). Accordingly, mean length of the population has been proposed as one of the SBI metrics to assess the status of exploited stocks (Ault et al., 2008, 2005), to estimate total mortality for assessing exploitation impacts on fish stocks (Gedamke and Hoenig, 2006; Then et al., 2018), or to estimate the spawning potential ratio in data-limited scenarios (Hordyk et al., 2015) as would be the case in most SSFs worldwide. Complementary to mean size, the shape of body size distributions is also considered in ecological studies at the population level (Ohlberger et al., 2013). For instance, the skewness of the distribution has been proposed as an early warning indicator of responses to anthropogenic disturbances in ecological systems (De Soyza et al., 1997; Orfanidis et al., 2010). Therefore, collating time-series of body size distribution descriptors in SSFs would allow tracing changes in stock status and/or exploitation levels. In fact, in data-limited situations, size data are often used to provide the first and simplest fishery advice, for instance, using length-based indicators and reference points based on body size information (Babcock et al., 2013; Cope and Punt, 2009).

One of the basic and most common management measures used to avoid growth and recruitment overfishing is the establishment of a minimum landing size (MLS) to limit fishing mortality by size class at an economically reasonable size. There are two main purposes of MLS strategy: to allow fish to spawn at least once using length at maturity as a reference (Myers and Mertz, 1998), and to catch fish at an optimum size for population growth (Froese et al., 2008). Unfortunately, management schemes are not always derived from proper biological reference points. As such, it has been demonstrated, in some instances, the biologically inadequacy of the MLS reference points, usually below the length at maturity, in the context of SSFs that generally target a variety of species with contrasting life histories (Stergiou et al., 2009; Tzanatos et al., 2008). Thus, it is timely to evaluate the implications of this misalignment for SSFs in the long-term.

In the European Union (EU) more than 80% of the fishing fleet is considered as small-scale. In coastal waters of the EU, Galicia (NW Spain) is one of the most fishery-dependent communities (Natale et al., 2013; Surís-Regueiro and Santiago, 2014) counting 4313 fishing vessels in 2020 of which 89% were registered as small-scale (accessed on 08/10/2020; https://www.pescadegalicia.gal/rexbuque/). Several studies have analysed the Galician fisheries, though most of them have dealt with socio-economic and governance issues (Cambiè et al., 2012; Macho et al., 2013; Molares and Freire, 2003), or addressed specific biological or ecological topics (Alonso-Fernández et al., 2017; Otero et al., 2008; Villegas-Ríos et al., 2014). However, there is a lack of studies dealing with the dynamics of the main fisheries resources of Galician SSFs, with the notable exception of recent works on catch and effort data obtained from onboard observers reporting temporal trends of relative abundance and fishing activity (Alonso-Fernández et al., 2019; Bañón et al., 2018). Therefore, in line with these previous analyses, this work aims to study the temporal trends and main drivers of body size at catch for the period 2000–2018 for a set of key commercial species, including 15 fish and 5 invertebrates (3 cephalopods and 2 crustaceans), exploited by the multi-gear small-scale fishing fleet operating off the Galician coast. Our objectives were i) to describe the species-specific variation of body size descriptors at the population level; ii) to investigate the factors that affect the variability of body size; iii) to study the common trends of the body size time series for the studied group of species; iv) to evaluate the potential effect of size selective exploitation patterns on stock status indicators, and v) to combine the body size and abundance indicators to assess the current performance of the studied species.

2. Material and methods

2.1. Study area and species

Galicia is located in the north-western corner of the Iberian Peninsula, between the river Eo (43° 32′ N, 7° 01′ W) and the river Miño (41° 50′ N, 9° 40′ W) comprising ICES Divisions 9.a and 8.c (Fig. 1). The combination of the topographic features and coastal orientation with the oceanographic conditions makes Galician waters be very productive (Arístegui et al., 2006) and able to support extensive costal fisheries and shellfish harvesting (Surís-Regueiro and Santiago, 2014). The Galician SSF is characterised for being a multi-gear and multi-species fishery. As such, roughly, 50 species are targeted for commercial purposes by the artisanal fleet (López-Veiga, 1992), yet only a few species can be considered key taxa from an economic point of view (Freire and García-Allut, 2000). In this study, we have focused on 20 relevant species for the small-scale fishing fleet including 15 fish, 2 crustaceans and 3 cephalopods (Table 1). Specific details regarding the criteria for the selection of the species included in this study can be found in a previous work (Alonso-Fernández et al., 2019).

2.2. Fishery dependent data

The Galician government through its Technical Unit of Artisanal Fisheries (Unidade Técnica de Pesca de Baixura, UTPB, in Galician) has monitored the small-scale fishing fleet since 1999. An on-board observer is assigned to a particular fishing vessel randomly selected from this sector covering the full set of multiple gears used in Galician waters and all along the geographical range (Fig. 1). UTPB observers record the total body size (total body length in fish, total carapace length in crustaceans and total mantle length in cephalopods, TL ± 0.1 cm, and total weight for *O. vulgaris,* TW ± 0.1 g) of both retained and discarded individuals. In a single trip/day each vessel usually performs several hauls. At each haul, observers record all basic operational data such as date, geographical position, fishing depth and gear type. Additionally, the observers include in the data base seafloor information based on the fishers' knowledge (Stephenson *et al.*, 2016). Three categories were considered in order to harmonize all the information gathered from the fishers during the on-board surveys: hard (rocky bottoms), mixed (mixture of rocky and soft bottoms) and soft (sand, mud, etc.) bottom types. During the first year of monitoring, 1999, the sampling protocol suffered from several changes, thus, we used data from 2000 onwards. Table 1 shows details about sampling effort.

2.3. Statistical analysis

A relatively large number of different fishing gears can catch a given species. Thus, before fitting any model, we selected the data for the most representative gear for each species (Table 1) in order to reduce sources of variation based on a balance among the following criteria: i) proportion of hauls with catch of each species and total number of individuals sampled ("the more the better", as an index of catchability), and ii) the spatio-temporal coverage of sampling (being sufficiently

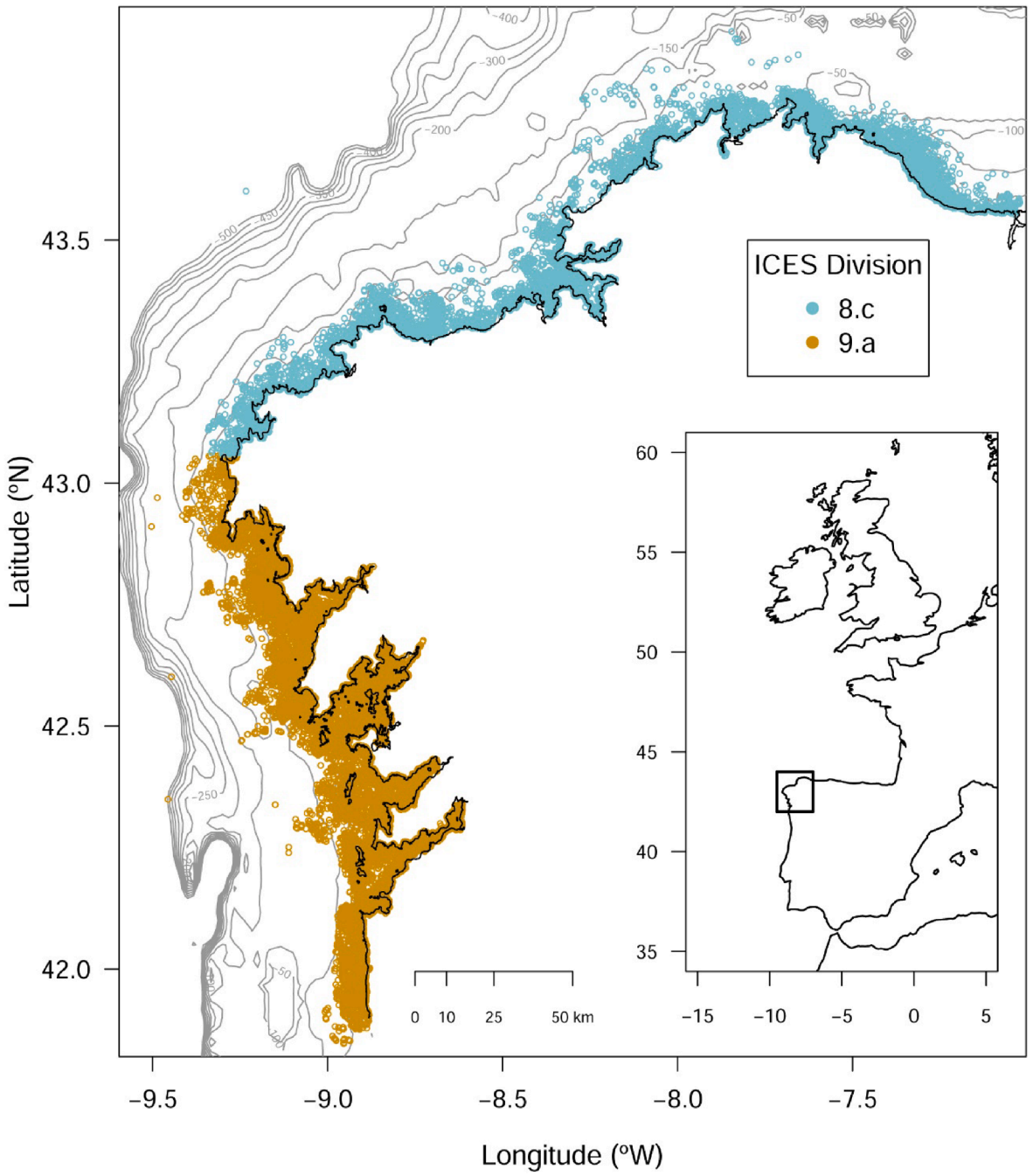

Fig. 1. Map of the study area (Galician coast, NE Atlantic) showing the distribution of all sampled hauls during the study period separated according to the two ICES divisions (orange dots 9.a and light blue dots 8.c).

large to build complete time series in both geographical zones) (Alonso-Fernández et al. 2019). Body size records were obtained from many boats performing multiple hauls per day or fishing trip as explained above. This implies potential correlation among body size records within hauls and boats pointing to the need of fitting linear mixed-effects models (LMM) (Thorson and Minto, 2015). Therefore, in order to study the changes in mean body size and account for potential correlation, the full model structure for each species was formulated as follows:

$$SZ_{ihb} = \alpha + \beta_1 ZN_{ihb} + \beta_2 YR_{ihb} + \beta_3 (ZN_{ihb} \times YR_{ihb}) + \beta_4 SF_{ihb} + \beta_5 DD_{ihb} + ns_1(DP_{ihb}, 2) + ns_2(DoY_{ihb}, 3) + a_{ihb} + b_{ihb} + \varepsilon_{ihb}$$

where SZ is the body size of an individual i (retained or discarded) caught in a haul h by a boat b. α is an intercept, and β's are the linear coefficients representing the effects of the following covariates: zone (ZN, either ICES division 8.c or 9.a, categorical), year of catch (YR, categorical), seafloor type (SF, categorical), and fish density (DD, continuous, log-transformed to meet normality). In the case of *L. vulgaris* seafloor type was not included as explanatory variable because all hauls were conducted in soft bottoms. DD was used as a surrogate of the species' abundance and was calculated dividing the number of individuals caught in a haul by the fishing effort put in that haul. The measure of effort varied depending on the gear type used: the number of pieces deployed for gillnets and trammel nets, the number of hooks for longlines, or the number of traps for trap fishing (Alonso-Fernández et al. 2019). *ns* denotes natural cubic splines fitted to account for non-linear responses for DoY (day of the year of catch) and DP (log-

Table 1
Summary information for the set of analysed species including the number of unique sampled vessels and fishing trips, the number of performed hauls and number of measured individuals showing the mean (±S.D.) body size for each species. Total body length in fishes, total carapace length in crustaceans and total mantle length in cephalopods, except for the case of *O. vulgaris* that are in weight. ImC = percentage of the catch (in numbers) below the length at maturity in the target fishing gear.

Species	Common name	Gear type	Gear name	Years	Vessels	Trips	Hauls	Individuals	Body size	ImC
Trisopterus luscus	Pouting	Gillnet	"Betas"	2000–2018	286	875	1804	52,999	21.60 ± 2.95 cm	24.53
Pollachius pollachius	Pollack	Gillnet	"Betas"	2000–2018	237	574	1001	10,023	34.01 ± 6.35 cm	95.74
Mullus surmuletus	Surmullet	Gillnet	"Betas"	2000–2018	259	736	1277	14,153	25.21 ± 3.32 cm	10.78
Dicentrarchus labrax	European sea bass	Longline	"Palangrillo"	2001–2018	54	231	810	3988	50.36 ± 9.76 cm	16.78
Conger conger	European conger	Longline	"Palangrillo"	2001–2018	46	83	179	2867	111.02 ± 24.82 cm	NA
Labrus bergylta	Ballan wrasse	Trammel net	"Miños"	2000–2018	354	1022	2175	13,520	33.06 ± 4.19 cm	1.39
Diplodus sargus	White sea bream	Trammel net	"Miños"	2000–2018	133	269	379	1114	31.49 ± 5.05 cm	7.16
Scophthalmus maximus	Turbot	Trammel net	"Miños"	2000–2018	170	342	434	745	36.11 ± 8.31 cm	92.00
Scophthalmus rhombus	Brill	Trammel net	"Miños"	2000–2018	190	403	512	927	36.95 ± 7.01 cm	48.87
Solea solea	Common sole	Trammel net	"Miños"	2000–2018	248	633	1048	4736	34.03 ± 5.24 cm	32.42
Solea senegalensis	Senegalese sole	Trammel net	"Miños"	2000–2018	217	477	724	2113	34.57 ± 4.55 cm	52.88
Pegusa lascaris	Sand sole	Trammel net	"Miños"	2000–2018	269	715	1228	6091	24.79 ± 3.30 cm	14.04
Platichthys flesus	European flounder	Trammel net	"Trasmallos"	2000–2018	144	290	407	1643	31.89 ± 4.55 cm	25.87
Scyliorhinus canicula	Lesser spotted dogfish	Gillnet	"Betas"	2000–2018	217	544	897	3969	50.40 ± 5.35 cm	80.66
Raja undulata	Undulate skate	Trammel net	"Miños"	2000–2018	235	510	692	1130	63.89 ± 16.85 cm	74.43
Sepia officinalis	Common cuttelfish	Trammel net	"Trasmallos"	2000–2018	298	1040	2966	24,844	15.45 ± 4.24 cm	81.92
Octopus vulgaris	Common octopus	Trap	"Nasa pulpo"	2000–2018	598	2302	15,297	165,149	1006.73 ± 776.42 g	98.88
Loligo vulgaris	European squid	Boat seine	"Boliche"	2000–2018	96	283	1177	28,837	8.62 ± 3.31 cm	64.13
Maja brachydactyla	Atlantic spinous spider crab	Trammel net	"Miños"	2000–2018	414	1364	3245	20,426	13.86 ± 2.75 cm	35.54
Necora puber	Velvet swimming crab	Trap	"Nasa nécora"	2001–2018	288	805	4469	59,649	5.03 ± 0.95 cm	23.70

transformed depth of the catch to meet normality) using 3 and 2 degrees of freedom, respectively. One reasonable interaction was further included in the models when data were sufficient: YR by ZN interaction, which would capture different temporal trends for each ICES division. Note that for one particular fishing gear, "Vetas" (gillnet), there is a secondary fishing modality ("volantillas") that, despite being very similar, it presents small technical differences that could potentially change the selectivity curve, thus, it was included as a factor in the model (Fm, Fishing modality) to account for that potential source of variation. a_{ihb} and b_{ihb} are random effects allowing for variation between boats and between hauls within boats, respectively. Both random effects were assumed to be normally distributed with mean 0 and variances σ_a^2 and σ_b^2. The residuals ε_{ihb} were assumed to be normally distributed random error with mean 0 representing within-haul and boat variation and variance σ. See **Supplementary Table S1** for details of model structure for each species. For the ease of interpretation, we estimated the rate of change in body size (in % year^{-1}) for each species and ICES division using the formula $\left(e^{(\alpha)} - 1\right) \times 100$, where α is the slope of a linear model over time with per year predictions of log-transformed SZ as response variable.

To further evaluate the coherence of the species-specific temporal trends in size between regions and detect common patterns in the time series, we applied a Dynamic Factor Analysis (DFA) (Zuur et al., 2003). DFA allows studying how multiple time-series of body size covary through time. DFA can also allow to model short, non-stationary time series in terms of common patterns and explanatory variables. In this case, we used average sea surface temperature by year and ICES division as a covariate. Optimum interpolation SST data available at weekly 1° latitude × 1° longitude grid resolution from a combination of satellite and in situ measurements (Reynolds et al., 2002) were obtained from the NOAA Earth System Research Laboratory (www.esrl.noaa.gov/psd/) for the study period.

Finally, aiming to study the status of this set of relevant species for the Galician SSFs we combined a series of species-specific indicators. In particular, we put together the estimated mean body size at catch obtained in the present study and the trends in abundance (updated up to 2018, Alonso-Fernández et al. 2019) aiming to assess the ongoing changes in the status of the studied species following the criteria depicted in Rochet et al. (2005) and Shin et al. (2005).

Current fisheries management of Galician SSFs depends on the department of maritime affairs of the regional government, and one of the main management measures is the establishment of a species-specific minimum landing size (MLS) (Xunta de Galicia, 2012). The MLS aims to control fishing mortality by size class, generally based on spawn-at-least-once policy in order to avoid recruitment overfishing (Myers and Mertz, 1998). In the case of Galician management measures, MLS does not match with available biological knowledge of the targeted species, with MLS being generally lower than length at maturity (L_{mat}) (**Supplementary Table S2**). This means that there is a significant fraction of juveniles that are potentially exploited by the artisanal fleet. Therefore, it is our aim to evaluate the potential effects of size selective exploitation on three indicators: the species' trends in mean body size, the shape of the size frequency distribution (measured by the skewness of the distribution with positive values indicating distributions with higher frequency of small individuals, while negatively skewed distributions show a higher frequency of large individuals), and the relative abundance of each species taken from Alonso-Fernández et al. (2019). In doing so, we first estimated a proxy of the fishing pressure on the immature fraction of the population by the selected fishing gear (ImC) calculated as the average percentage of the catch, retained and discarded (in numbers), below the length at maturity using the size

frequency distribution of all sampled individuals in each geographic zone (pooled data for years 2000–2018). Second, we calculated the annual rate of change for the predicted estimates of body size at catch (eq. 1 depicted above) and for the trends in relative abundance taken from Alonso-Fernández et al., (2019) and updated up to 2018 to cover the same time period (**Supplementary Figs. S1–S3**). Third, we estimated the temporal trend in the skewness of the size frequency distributions of the catch for each species fished by the selected fishing gears in each ICES division (**Supplementary Fig. S4–S5**). We analysed the relationship of the ImC index with the three species-specific indicators, that is, the rate of change in body size, the rate of change in relative abundance, and the slope of the skewness over time.

All treatment of data was performed with the R language, R version 3.5.0 (R Development Core Team, 2018), and using the packages "lme4_1.1-17" (Bates et al., 2015) and "MARSS_3.10.4" (Holmes et al., 2012).

3. Results

3.1. Frequency distributions of body size

Body size distribution covered the whole range of sizes, from juveniles to adults, in most cases (Figs. 2–3). The level of individuals above MLS in the catch for all the species analysed was high, with an average of 86% of the individuals caught. Only trap fisheries (*N. puber* and *O. vulgaris*) reported<50% of the catch (in numbers) above MLS, rendering higher levels of discarded individuals. Discarded individuals typically were within the smallest sizes and usually below the length at maturity, except for *S. canicula*. The retained catch comprised the larger sizes, however, part of the retained individuals were below the length at maturity. Overall, the average proportion of total individuals caught below L_{mat} (ImC) was 46.4% ranging from 1.4% in *L. bergylta* to 98.9% in *L. vulgaris* (Figs. 2–3 and Table 1). The ImC was higher than 50% in 8 of the studied species (*S. senegalensis*, *S. officinalis*, *R. undulata*, *S. canicula*, *O. vulgaris*, *S. maximus*, *P. pollachius* and *L. vulgaris*) (Figs. 2–3).

The shape of the frequency distributions of size at catch were roughly normal in all cases for the whole set of measured individuals; however, this shape showed considerable variation among years within species (**Supplementary Figs. S4—S5**). More specifically, the skewness of the size distribution significantly decreased just for *R. undulata* in the ICES 8.c division. *S. solea*, *P. lascaris* and *L. bergylta* in ICES 8.c and *L. bergylta* in ICES 9.a showed significant increments in the skewness of the size distribution (**Supplementary Figs. S4—S5**).

3.2. Long term-trends in body size

In general, normalized residuals of body size models did not show critical departures from normality or further heterogeneity issues, and random effects were reasonably normally distributed for all models (**Supplementary Figs. S6–S25**). However, in a reduced number of cases, in particular for *P. lascaris, R. undulata, O. vulgaris, Loligo vulgaris* or *M. brachydactyla*, random effects showed small deviations from the optimal distribution.

Body size variability showed significant fluctuations from year to year for all studied species with the exception of *S. canicula*, *D. sargus*, *S. solea*, *S. senegalensis*, *S. maximus* and *S. rhombus* (Fig. 4). Overall, body size at catch showed relatively low rates of change (**Supplementary Fig. S1**). However, there were several species that presented consistent trends along the study period (Fig. 4 and **Supplementary Fig. S1**). Only *M. brachydactyla* (−0.43% $year^{-1}$, 95% C.I.: −0.64 to − 0.22), *S. officinalis* (−0.51% $year^{-1}$, 95% C.I.: −0.84 to − 0.18) and *O. vulgaris* (−0.76% $year^{-1}$, 95% C.I.: −1.37 to − 0.14) showed negative trends in the ICES division 8.c. Positive trends where present in ICES 8.c for *T. luscus* (0.48% $year^{-1}$, 95% C.I.: 0.25 to 0.70), *P. pollachius* (0.33% $year^{-1}$, 95% C.I.: 0.02 to 0.64), *M. surmuletus* (0.56% $year^{-1}$, 95% C.I.: 0.34 to 0.78), *R. undulata* (0.88% $year^{-1}$, 95% C.I.: 0.42 to 1.34) and *C. conger* (0.89% $year^{-1}$, 95% C.I.: 0.16 to 1.62). In the ICES 9.a we found significant positive trends for *C. conger* (1.01% $year^{-1}$, 95% C.I.: 0.22 to 1.81) and *N. puber* (0.53% $year^{-1}$, 95% C.I.: 0.33 to 0.73) (**Supplementary Fig. S1**). Zonal differences between north and south were not important with the unique exception of *S. officinalis* that showed consistently larger individuals in ICES 8.c (Fig. 4).

3.3. Seasonal patterns in body size

In general, most species showed significant seasonal variation in mean body size. However, *C. conger*, *D. sargus*, *S. maximus, P. flesus, S. canicula* and *R. undulata* did not show any particular intra-annual pattern (Fig. 5 and Table 2). The general picture was the occurrence of smaller individuals during summer months (*T. luscus*, *P. pollachius*, *M. surmuletus*, *L. bergylta*, *S. solea*, *P. lascaris*, *O. vulgaris*, *S. officinalis, M. brachydactyla* and *L. vulgaris*), while other species showed different patterns, for instance, mean body size of *S. rhombus* was smaller during spring, and for *D. labrax, S. senegalensis* and *N. puber* smaller individuals were fished during late autumn/early winter (Fig. 5 and Table 2).

3.4. Density, depth and habitat effects

Body size at catch was negatively related to the species density with hauls where catch rates were higher showing smaller average body sizes. However, we found some non-significant exceptions, e.g. *C. conger* and *L. bergylta* (Table 2).

The body size of the individuals caught were significantly related with depth in the case of *T. luscus*, *P. pollachius*, *M. surmuletus*, *L. bergylta*, *D. sargus*, *S. maximus*, *S. rhombus*, *S. solea*, *S. officinalis*, *O. vulgaris*, *M. brachydactyla* and *N. puber*, with larger individuals found in deeper waters (**Supplementary Fig. S26**). This relationship, however, was the opposite for the case of *P. lascaris* and *S. canicula* (**Supplementary Fig. S26**). No significant relationship was found for *D. labrax*, *C. conger*, *S. senegalensis*, *P. flesus*, *R. undulata* and *L. vulgaris* (Table 2 and **Supplementary Fig. S26**).

Habitat affinities varied among species. Smaller individuals of *T. luscus*, *P. pollachius*, *M. surmuletus*, *S. rhombus*, *S. solea*, *S. canicula*, *R. undulata*, *S. officinalis* and *M. brachydactyla* were more prone to be caught in soft bottoms. Only *O. vulgaris* showed significantly higher body size in soft substrates. Species such as *D. labrax*, *C. conger*, *L. bergylta*, *S. maximus*, *S. senegalensis*, *P. lascaris*, *P. flesus* and *N. puber* did not show any particular preference between hard and soft bottoms (Table 2).

3.5. Common trends in body size

The main common trend in mean body size at catch showed contrasting patterns over time between ICES divisions (Fig. 6 and **Supplementary Fig. S27—S28**). DFA models did not improve with the addition of average sea surface temperature as a covariate using any of the time lags applied (no lag, 1 year lag, 2 year lag). In general, for ICES division 8.c we found a steady positive pattern of the main common trend of body size time series. This increasing trend was positively related mainly with *T. luscus*, *P. pollachius*, *M. surmuletus*, *C. conger*, *S. canicula* and *R. undulata*. By contrast, in ICES division 9.a the main common trend increased until 2002, then it was relatively stable during the next five years, and it finally declined until the present. *T. luscus*, *P. pollachius*, *M. surmuletus*, *D. labrax*, *S. rhombus*, *O. vulgaris* and *S. officinalis* were the species with higher correlation with this common trend. Nonetheless, for both zones, it must be noticed that the factor loadings on the dominant trends were relatively weak (Fig. 6 and **Supplementary Fig. S27—S28**).

3.6. Indicators of stock status

The combination of the rates of change in body size obtained in the present study, with the trends in relative abundance taken from a

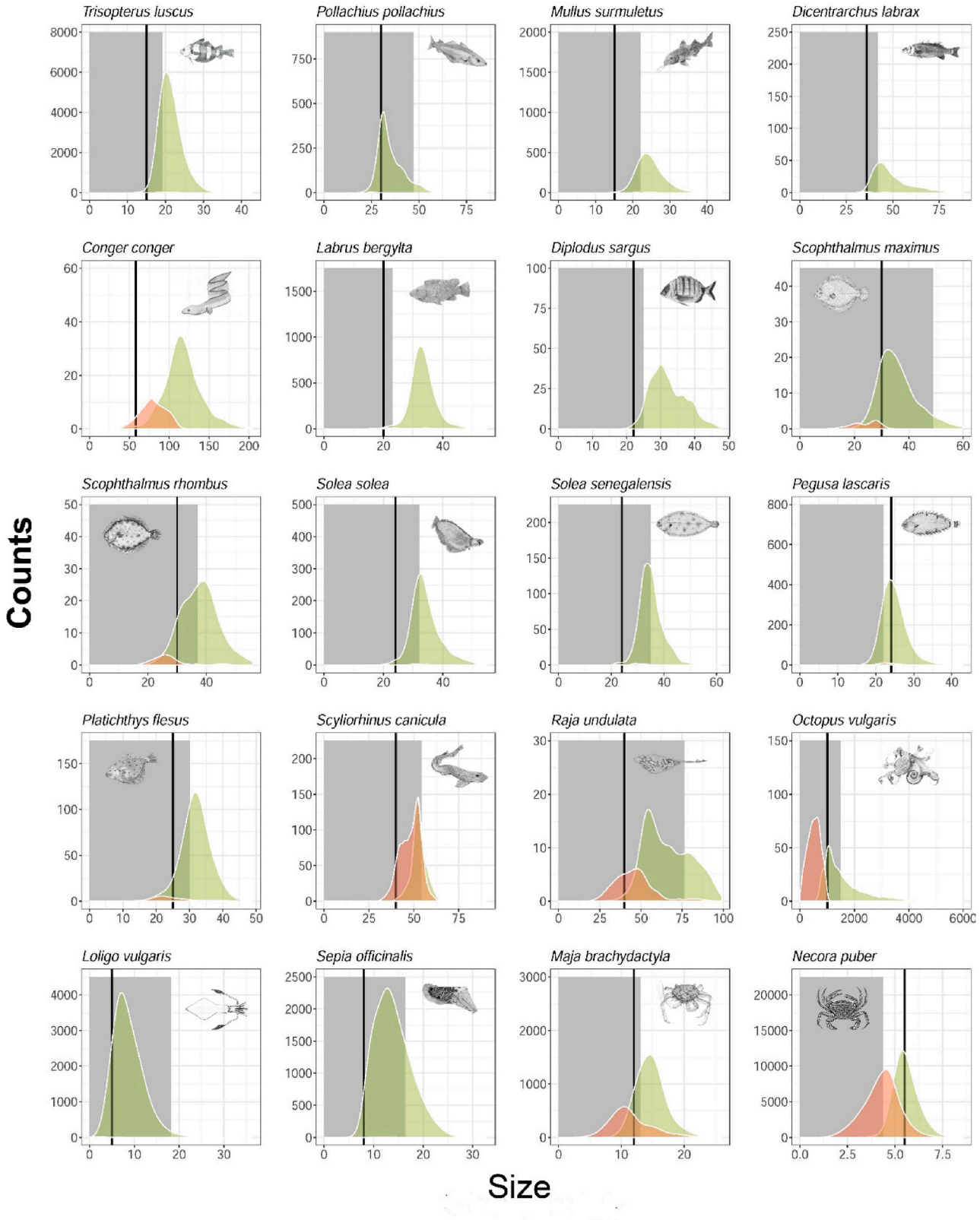

Fig. 2. Size frequency distribution of retained (green) and discarded (red) individuals in sampled hauls in ICES division 9.a. The grey shaded area represents sizes under length at maturity for each species, and the vertical black lines show the minimum landing size (MLS). Body size units are in cm except for the case of *O. vulgaris* that are in g (total weight).

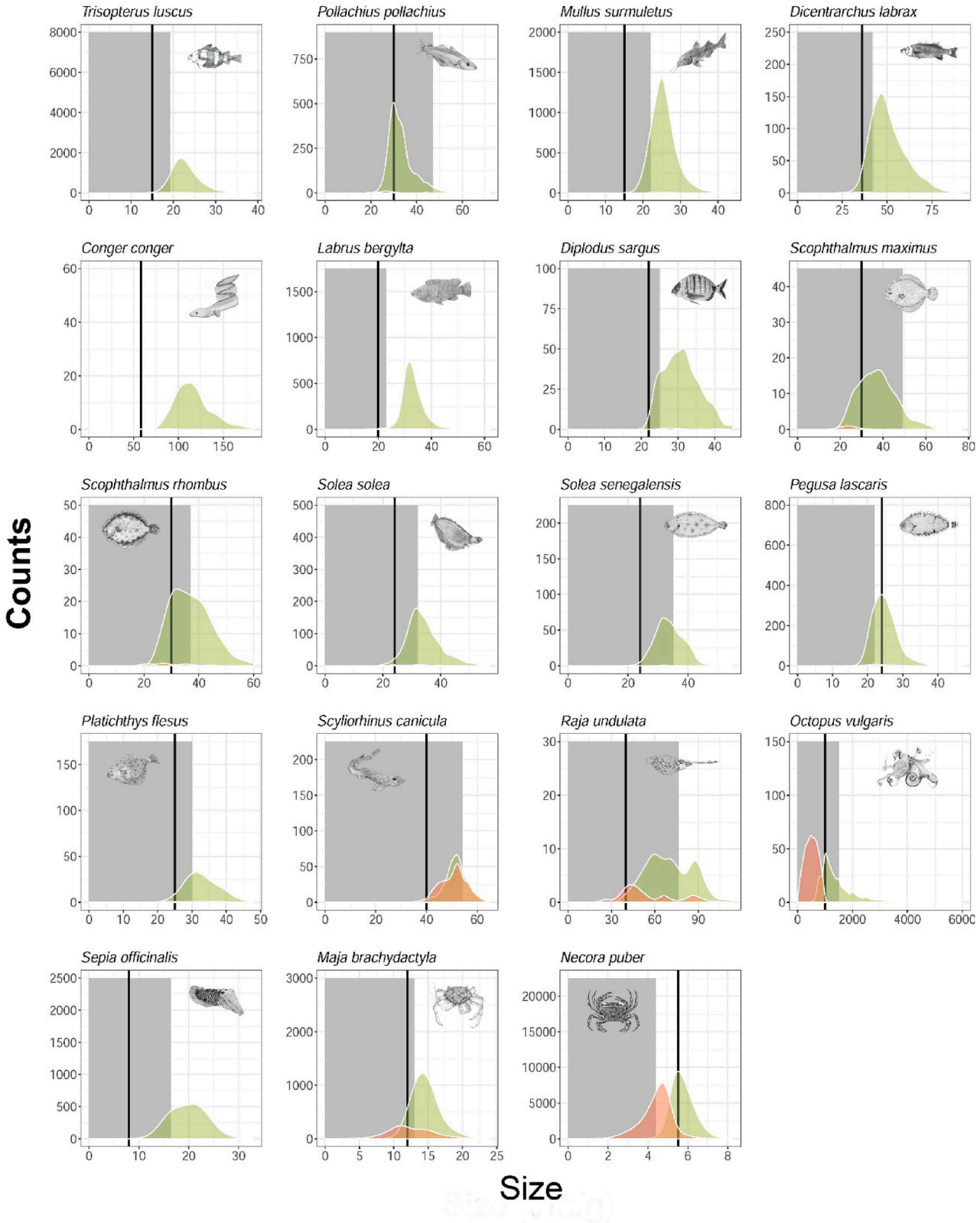

Fig. 3. Size frequency distribution of retained (green) and discarded (red) individuals in sampled hauls in ICES division 8.c. The grey shaded area represents sizes under length at maturity for each species and the vertical black lines show the minimum landing size (MLS). Body size units are in cm except for the case of *O. vulgaris* that are in g (total weight).

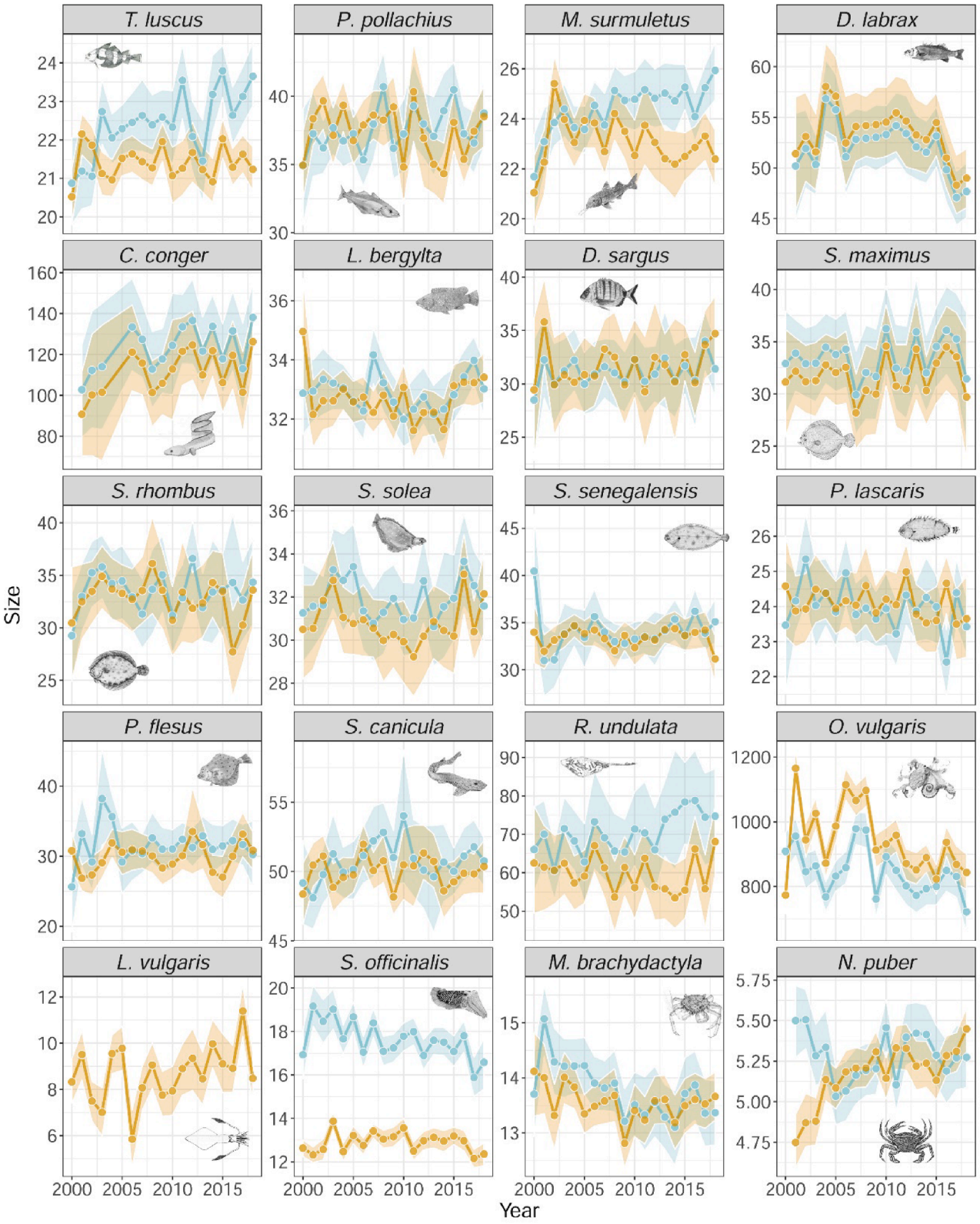

Fig. 4. Time series of predicted body size at catch for the 20 species analysed from 2000 to 2018 in the Galician coast (NE Atlantic). Light blue lines indicate ICES division 8.c, and the orange lines show ICES division 9.a. Shaded areas represent 95% confidence. Values for all explanatory variables used for predictions for each species' model and units of the abundance indices are shown in **Supplementary Table S3**. Body size units for *O. vulgaris* are in g (total weight), and in cm for the rest of species.

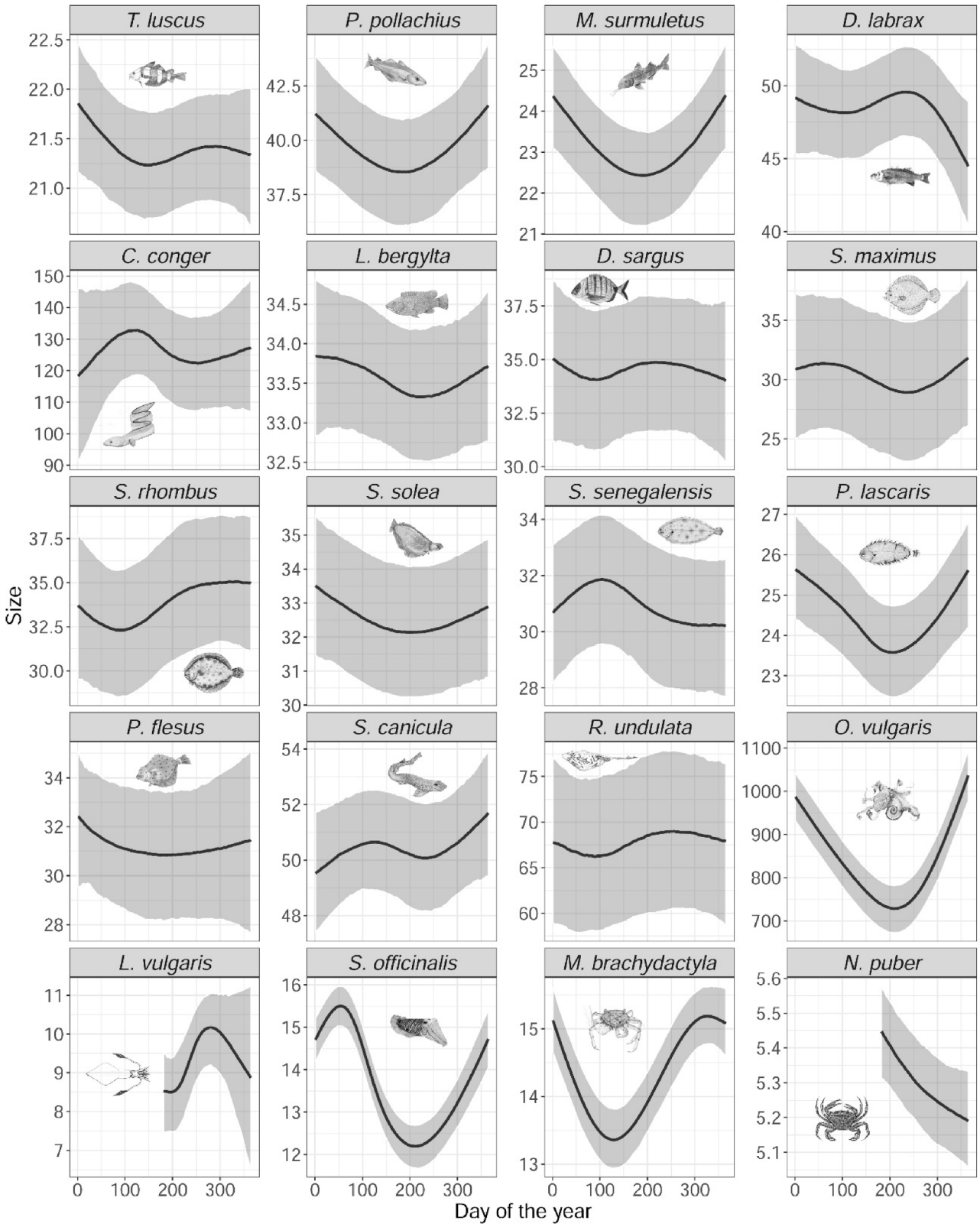

Fig. 5. Estimated (±95C.I.) seasonal variation in body size at catch for the 20 species analysed in the Galician coast (NE Atlantic). The fixed values for all explanatory variables used for predictions for each species' model and units of the abundance indices are shown in **Supplementary Table S3**.

previous work and revisited here (**Supplementary Fig. S1 and S3**), showed that, on average, the performance of this group of exploited species in the Galician coast was relatively stable for 15 species in ICES 9.a and 12 in 8.c, 70 and 60%, respectively (Table 3). Nevertheless, 5 species in ICES 9.a (*T. luscus*, *S. maximus*, *R. undulata*, *S. officinalis* and *L. vulgaris*) and 8 in 8.c (*P. pollachius*, *M. surmuletus*, *S. maximus*, *S. rhombus*, *R. undulata*, *S. officinalis, O. vulgaris* and *M. brachydactyla*) showed some signs of a worsening of their status.

Table 2
. Summary of the fitted models to each species' individual body size showing the statistical significance for each covariate (i.e. fixed effects, except the annual trends) included in the formulation (* < 0.05; ** < 0.005; *** < 0.0005, otherwise non-significant). NA indicates that a given variable was not included in the model. Arrows indicate the direction of each variable's effect (↗ = positive relationship, ↘ = negative relationship). Fm = fishing modality ("volantillas"); DD = fish density; DP = depth of catch; SF = seafloor type; DoY = day of the year of catch. Seasonal (DoY) and depth (DP) effects are graphically represented in Fig. 5 and **Supplementary Fig. S26**.

Species	Fm	DD	DP	SF (mixed)	SF (soft)	DoY
T. luscus	↗(***)	↘(***)	(↗***)	↘(***)	↘(***)	(*)
P. pollachius	↗(***)	↘0	↗(***)	↘(**)	↘(***)	(***)
M. surmuletus	↗(***)	↘(***)	↗(***)	↘(***)	↘(***)	(***)
D. labrax	NA	↘0	↗0	↘0	↘0	(*)
C. conger	NA	↗0	↗0	↘0	↗0	0
L. bergylta	NA	↗0	↗(**)	↗0	↘0	(*)
D. sargus	NA	↘0	↗(***)	↘ (*)	↘0	0
S. maximus	NA	↘(*)	↗(***)	↘0	↘ 0	0
S. rhombus	NA	↘(*)	↗(***)	↗0	↘ (*)	(***)
S. solea	NA	↘(***)	↗(***)	↘0	↘(***)	(*)
S. senegalensis	NA	↘(***)	↗0	↗0	↘0	(***)
P. lascaris	NA	↘0	↘(***)	↘0	↘0	(***)
P. flesus	NA	↘(*)	↘0	↗0	↘0	0
S. canicula	↗(***)	↘(**)	↘(***)	↘0	↘(***)	0
R. undulata	NA	↘0	↗0	↘(**)	↘(***)	0
S. officinalis	NA	↘(***)	↗(***)	↗0	↘(**)	(***)
O. vulgaris	NA	↘(***)	↗(***)	↗ (*)	↗(***)	(***)
L. vulgaris	NA	↘(***)	↗0	NA	NA	(***)
M. brachydactyla	NA	↘(***)	↗(***)	↘0	↘(***)	(***)
N. puber	NA	↘(**)	↗(***)	↘0	↗0	(***)

3.7. Biological reference points and stock status indicators

The ImC did not show any correlation with either the rate of change in body size or the rate of change in abundance (**Supplementary Fig. S29**). Regarding the shape of body size distributions, the ImC showed a negative relationship with the trend in skewness (Fig. 7**a**), meaning that species that showed a larger proportion of immature individuals in the catch also showed a more negative slope of the skewness time trend (i.e. higher tendency to larger individuals in the catch). Furthermore, the relative abundance rate of change was positively related with the slope of the skewness time trend, that is, those species with higher positive trends in abundance showed higher positive trends in skewness (i.e. higher tendency to smaller individuals in the catch) (Fig. 7**b**). Finally, we did not find a significant relationship between the body size rates of change and skewness trend (**Supplementary Fig. S30**).

4. Discussion

4.1. Long-term and common trends in body size

It is well known that anthropogenic stressors, such as fishing, can generally lead to lower average sizes (Levin et al., 2006; Charbonneau et al., 2019), and recruitment failures (Ottersen, 2008). However, our analysis of the trends in body size for a set of 20 coastal exploited species after controlling for a variety of intrinsic and extrinsic factors showed that, in general, the inter-annual variability remained relatively stable for most species and geographical zones in Galician SSFs. Estimated declining trends were low, however, *M. brachydactyla*, *S. officinalis* and *O. vulgaris* showed a consistent tendency towards smaller sizes in ICES division 8.c. Thus, our results do not point to a generalized trend

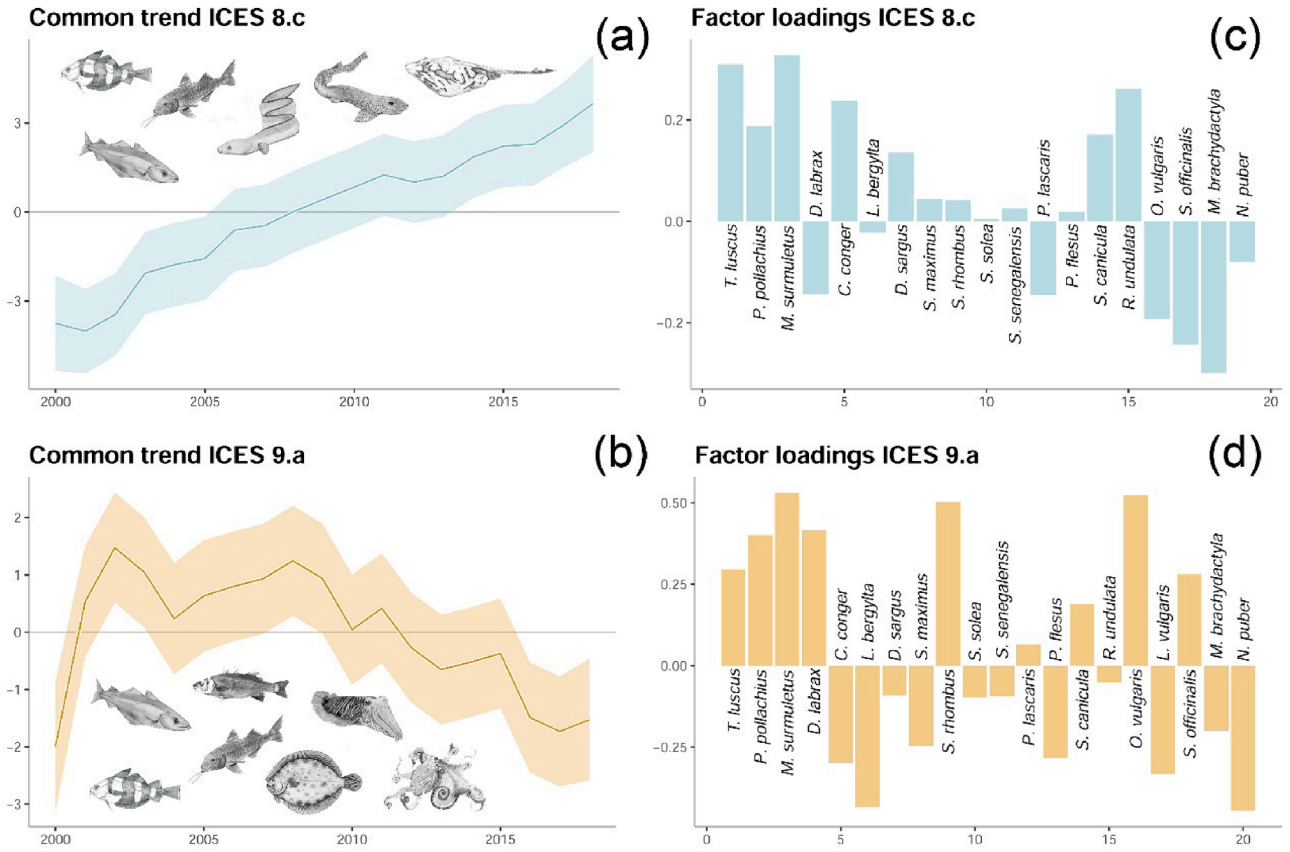

Fig. 6. Dynamic factor analysis (DFA) of the estimated body size at catch for the whole set of studied species in ICES division 8.c (a) and 9.a (b). Shown are also the loadings of each species on the common trend in ICES division 8.c (c) and 9.a (d).

Table 3
Combined trends in population indicators. SBI = body size indicator (Fig. 4); Nr = relative abundance index (**Supplementary Fig. S2**). Symbols: = no significant trend; ↗ positive trend; ↘ negative trend. Grey cells highlight a combination of indicators that point to a deleterious stock status trend.

Species	ICES 9.a		ICES 8.c	
	SBI	Nr	SBI	Nr
Trisopterus luscus	=	↘	↗	=
Pollachius pollachius	=	=	↗	↘
Mullus surmuletus	=	=	↗	↘
Dicentrarchus labrax	=	=	=	=
Conger conger	↗	=	↗	=
Labrus bergylta	=	=	=	=
Diplodus sargus	=	=	=	=
Scophthalmus maximus	=	↘	=	↘
Scophthalmus rhombus	=	=	=	↘
Solea solea	=	=	=	=
Solea senegalensis	=	=	=	=
Pegusa lascaris	=	=	=	=
Platichthys flesus	=	=	=	=
Scyliorhinus canicula	=	↗	=	↗
Raja undulata	=	↘	↗	↘
Sepia officinalis	=	↘	↘	=
Octopus vulgaris	=	=	↘	=
Loligo vulgaris	=	↘	=	=
Maja brachydactyla	=	=	↘	=
Necora puber	↗	=	=	=

towards a smaller mean body size as a response to exploitation for this group of coastal species over the last two decades. Temporal patterns can be the result of other factors though. Schmitter-Soto et al. (2018) observed increases in maximum length over the years in several species despite human development in the Mexican Caribbean associated to MPAs, while Barley et al. (2017) in Australian coral reefs, and Ohlberger et al. (2019) in chinook salmon from central California to western Alaska, found a decrease in body size in response to an increase in top predator abundance. That said, we acknowledge that there are some limitations regarding our fishery-dependent data that would merit a species-specific closer look, which is beyond the scope of this study. One of the main concerns would be the lack of age data, a relevant source of information to deal with different growth patterns within populations (Ohlberger et al., 2013). The lack of this biological information hampers disentangling if observed changes in body size are responses to changes in stock size structure (i.e. size selective fishing) (Ottersen, 2008) or to changes in individual growth rates (i.e. density dependence or responses to the environmental conditions) (Rogers et al., 2011). Moreover, the role of gear selectivity is disregarded in our analyses. SSF gears such as gillnets and trammel nets commonly used by this fleet tend to be characterised by dome-shape selectivity curves. Dome-shape mortality patterns can exert potential benefits associated with both fast and slow growth (Swain et al., 2007; Kuparinen et al., 2009), and dome-shape selectivity tend to have a lower influence on the dynamics of mean size than logistic selectivity curves (e.g. trawling in industrial fisheries) (Erzini et al., 2006). Furthermore, the relatively short length of the time series of the observed body size trends makes it difficult to compare the most recent trends in body size with the times preceding the full development of the SSFs in the study area. Nonetheless, the overall temporal stability in body size observed here may serve as baseline for future prospects.

Regarding common patterns among the studied species, we found differences between northern (ICES 8.c) and southern coast (ICES 9.a) of Galicia in the main common trends of body size. Differences in common trends (positive in the north and negative in the south) may indicate differences in local conditions among geographical regions along the Galician coast (Alonso-Fernández et al., 2019). We did not find significant effects of sea surface temperature variations though. However, these differences could arise due to different regimes and levels of exploitation as it was previously reported for a particular small scale fisheries in the area, i.e. octopus trap fishery (Bañón et al., 2018). Moreover, the combination of the topographic features and coastal orientation with the oceanographic conditions divides the Galician coast into three domains: the western coast (ICES division 9.a), and the central coast (known as Ártabro Gulf) and the northern coast (known as Cantabrian Sea) included in the ICES division 8.c. They are characterized by differences in the upwelling strength and timing and primary productivity (Alvarez et al., 2012; Álvarez et al., 2011), thus current changes in the local oceanographic conditions in the Galician coast (Álvarez-Salgado et al., 2008) could have different impacts on growth, natural

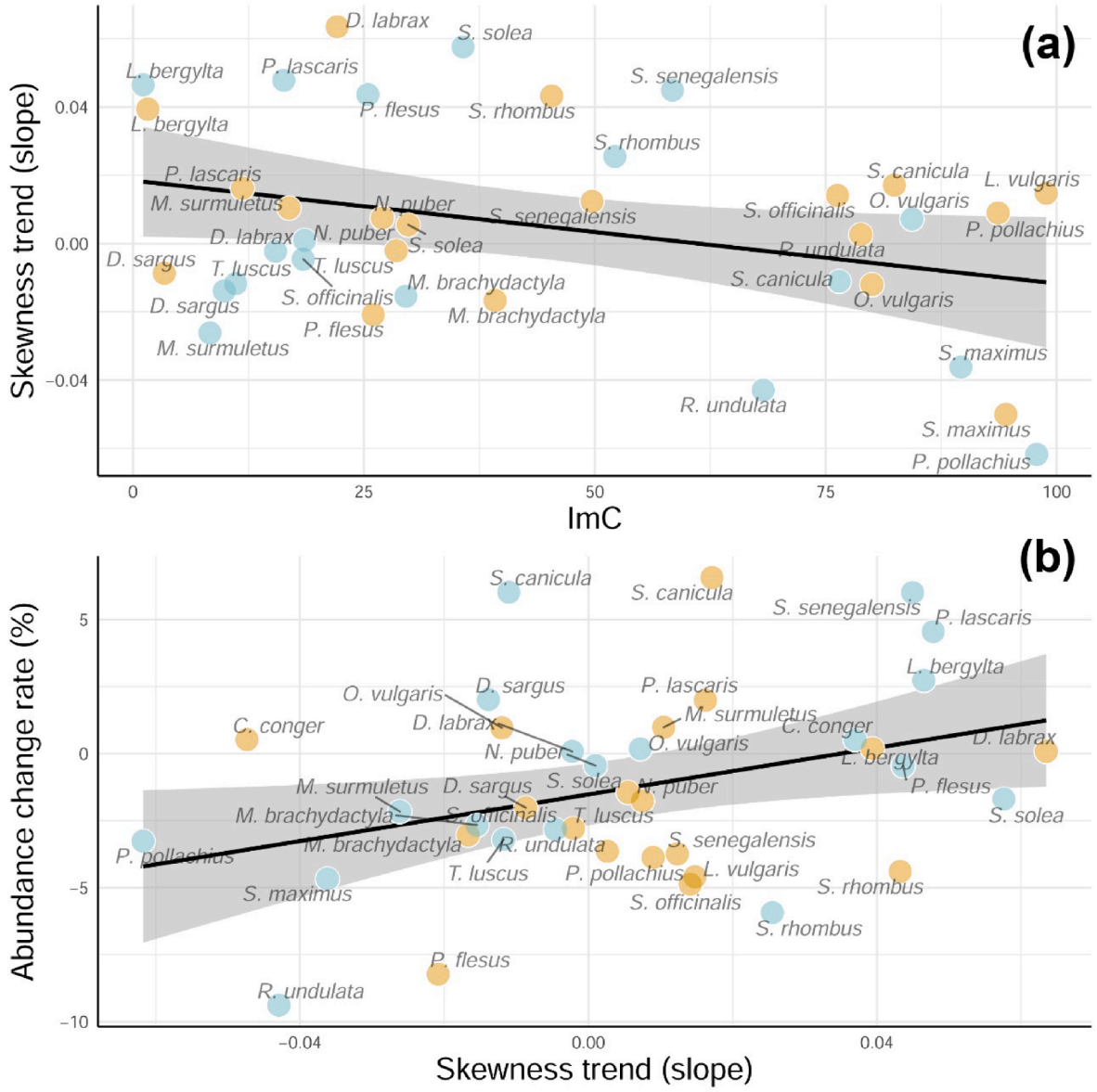

Fig. 7. Relationship between the slope of the time trend of skewness of body size distribution and the proportion of immature individuals caught (in number, ImC) (a). Relationship between the rate of change of relative abundance (% · year^{-1}) with the slope of the time trend of skewness of body size distribution (b). Light blue dots indicate ICES division 8.c, and the orange dots show ICES division 9.a. An extreme value of relative abundance rate of change lower than −20% (*S. maximus* in ICES 9.a) was omitted for clearer visualization.

mortality or recruitment success in the local populations not accounted for in our models. Therefore, more detailed analyses using local environmental conditions and anthropogenic pressures deserve a closer attention in order to identify the main drivers of geographical differences at the species level.

4.2. Seasonal dynamics of body size

A ubiquitous pattern in body size found in our work and others would be the seasonality, which is present in most of the biological an ecological features in temperate species (Munro et al., 1990). Seasonal variation in body size at the population level may represent a species-specific response to internal biological cycles and their interaction with the dynamics of the SSFs. For instance, seasonal changes in fish body size can be a mixture of responses to variations in reproductive timing, recruitment and/or growth but also to changes in gear catchability because of individual behaviour (Corgos et al., 2007; Alonso-Fernández et al., 2017). The individuals of certain species targeted by the SSF, such as the pollack, are bigger during their reproductive period in winter (Alonso-Fernández et al., 2014). Seasonal patterns of *P. pollachius* in Galicia seem to be related to an offshore-inshore migration of bigger females to reproduce in coastal shallow waters increasing the species vulnerability to artisanal fishing gears (Alonso-Fernández et al., 2014). Mating behaviour can be also a good predictor of size selective changes in catchability as would be the case for *O. vulgaris* (Alonso-Fernández et al., 2017). During summer months, bigger *O. vulgaris* females disappear from the catches during the period of parental care, coinciding also with the period of higher recruitment (Alonso-Fernández et al., 2017), hence, reducing significantly mean size at catch. Furthermore, seasonal molting also predicts changes in size selective catchability in crustaceans such as *M. brachydactyla*, for which terminal moult takes place generally in summer (June-September) when size at catch decreases significantly (Corgos et al., 2007). Species with short life cycles, mainly composed by a single cohort, generally show growth patterns in the catch profile with an increase in mean size as the fishing season progresses, as would be the case of *L. vulgaris* (Guerra and

Rocha, 1994). Migration patterns along ontogeny can also be related to seasonal variations in body size, for instance, in the French Atlantic coast, juveniles of *S. officinalis* migrate from inshore nursery grounds to offshore deeper waters and stay there for winter (Wang et al., 2003).

4.3. Density, depth and habitat effects

Shoaling behaviour in fish is suggested to be body size dependent (Hoare et al., 2000; Ward and Krause, 2001). Random effects at the haul level revealed a high average intraclass correlation (0.74 ± 0.08) in body size measures suggesting a size class grouping for all the species. Besides this strong similarity in individual body size records in a given haul, we found a negative relationship between body size and the number of fish caught in a haul for all species. This link potentially reflects a progressive reduction of the size of the shoals as the fish grows, as has been demonstrated previously in sparid fishes (Macpherson, 1998). Furthermore, the negative relationship could be partially explained also by a density-dependent effect, a common mechanism in the regulation of fish populations that affects fish growth (Lorenzen and Enberg, 2002), i.e., competition at high population densities reduces body growth (Crozier et al., 2010; Jensen et al., 2000; Ohlberger et al., 2013). We are aware that our findings have some limitations mainly because the lack of age data and the density index used in the models is a rough indicator of local abundance or fish size grouping, thus, we cannot attribute the observed density-dependent effects to any one of the two possible mechanisms, shoaling behaviour or detrimental effects of density on growth.

The bigger-deeper phenomenon, larger individuals in deeper waters, seems to be ubiquitous in coastal species in Galicia, with the exception of *S. canicula*, and *P. lascaris*, which are likely related to life cycle characteristic. Females of *S. canicula* ascend to shallower waters for egg laying in suitable bottom substrates, while juveniles seem to go deeper as they grow (Ellis and Shackley, 1997; Muñoz-Chápuli, 1984). *P. lascaris* has a shallower distribution than the rest of the pleuronectiforms studied here (Fernández-Zapico et al., 2017), and the distribution of its eggs suggests that the spawning grounds are located from 0 to 50 m depth (Ozyurt et al., 2018). Exceptions apart, bathymetric gradients in body size seem to be common and could be ascribed to several processes such as the finding of better feeding opportunities, predator avoidance, or more optimal temperature conditions for growth and reproduction (Audzijonyte and Pecl, 2018). Other factors like fishing exploitation have been suggested to induce ontogenic-like deepening in Atlantic cod in the eastern Scotian Shelf (Frank et al., 2018), though this pattern seems to be controversial as Baudron et al. (2019) did not find evidence that deepening in Northeast Atlantic stocks was driven by fishing intensity. In line with this, Galician SSFs suffered a slightly decreased of fishing effort along the last two decades (Bañón et al., 2018; Alonso-Fernández et al., 2019), thus, it is unlikely that the studied species would move to deeper waters along ontogeny in response to fishing intensity. Nonetheless, the general pattern of ontogenic deepening has been also found in SSF catches in the Mediterranean Sea (Tzanatos et al., 2008), which agree also with general trends for demersal fish communities in SE Atlantic and NW Mediterranean Sea (Macpherson and Duarte, 1991).

Another aspect of heterogeneous spatial distribution would be the effect of sea bottom type on body size segregation. Although less prevalent than ontogenic deepening, our study reveals that, for half of the species, smaller fish tended to be associated to soft bottoms, with the exception of *O. vulgaris* for which larger individuals tended to prefer soft bottoms (Katsanevakis and Verriopoulos 2004). Species' associations to specific habitats can be the result of different causes. For instance, selection of an appropriate spawning habitat can induce spatial differences in the distribution of small juveniles and big mature individuals as observed for cuttlefish which prefers hard bottom substrates to lay eggs (Guerra et al., 2016). Feeding habitat can also vary with body size in response to prey preferences and availability, for instance, the stomach contents of juveniles of *S. canicula* revealed the presence of several species that inhabited soft sediments in the eastern central Adriatic Sea (Šantić et al., 2012). Therefore, this study suggests the potential existence of ontogenetic habitat shifts linked to spawning grounds or feeding habitats as has been observed for similar fish communities in the Mediterranean Sea (Tzanatos et al., 2008).

4.4. Indicators of stock status

Ideally, SBI trends should be interpreted in conjunction with complementary information such as abundance indices to make less speculative inferences about stock status (Bellail et al., 2003; Jennings and Dulvy, 2005; Rochet et al., 2005). The combination of indicators, mean body size and standardized abundance, presented in this study provides a general picture pointing to a certain stability during the study period. Indeed only 5 species in ICES division 9.a (*T. luscus*, *S. maximus*, *R. undulata*, *S. officinalis* and *L. vulgaris*) and 8 species in ICES division 8.c (*P. pollachius*, *M. surmuletus*, *S. maximus*, *S. rhombus*, *R. undulata*, *O. vulgaris*, *S. officinalis* and *M. brachydactyla*) showed signs of some degree of potential deterioration. However, definition of a desirable trend can only be achieved in comparison with a known baseline, an initial state assessment and also a management objective (Jennings and Dulvy, 2005). For instance, a stationarity situation is acceptable in a non-impacted initial status (Rochet et al., 2005). Therefore, our results and interpretation could be affected by the "shifting baseline syndrome" (Pauly, 1995). However, to our knowledge, there is a lack of comprehensive baselines in our study area with the exception of a work that suggested dramatic decreases in body size in reef species pointing to a near collapse of the coastal fish community of Galicia (Pita and Freire, 2014). Those authors used a historic archive (1953–2007) of recreational spearfishing competitions to infer changes in population demography of a limited number of species based on the maximum weight of the captures. The claimed decreasing trends in that study were probably driven by the scarcity of data at the beginning of the time series before the 1980 s when spearfishing competitions were uncommon. After that time, trends turned to be relatively stable during the following three decades for the species targeted by the spear fishers concurring with the stability that we observe in more recent years which does not point by no means to a collapse of the exploited community in these waters. Apart from that, although there is no stock assessment for any of the analysed species, the available ICES advice on fishing opportunities seems to concur with our results. More specifically, commercial landings of *P. pollachius* and *D. labrax* have been stable for the last two decades in the Bay of Biscay and Atlantic Iberian waters (ICES., 2019a; ICES, 2019b). Catches of *S. solea* shows a relatively stable period from 2010, and the stock size indicator of *S. canicula* has shown an increasing trend since 2004 in the Cantabrian Sea and Atlantic Iberian waters (ICES 2019c, 2019d); while *M. surmuletus* shows a decline in landings since 2007 in the North Sea, Bay of Biscay, southern Celtic Seas, and Atlantic Iberian waters (ICES, 2020). Therefore, although more and better data are required to conduct a proper assessment (Dowling et al., 2019), our two-decade study, in conjunction with indirect information for some of the species analysed here exploited by more industrial fleets, points to a stable performance of some of the most important artisanal resources in the Galician coast. That said, it is important to note that the multispecies and multigear nature of Galician fisheries (each vessel can license up to five types of fishing gears that might shift during the fishing season) provides fishers the capacity to adapt fishing strategies to the status of the different fishery resources, which could, to some extent, limit the overexploitation of certain populations.

4.5. Biological reference points and stock status indicators

The shape of body size distributions, the skewness, has been considered in ecological studies in order to assess the impact of anthropogenic stressors on population structure in several taxa (Ohlberger et al., 2013; Orfanidis et al., 2010). Despite the general low level

of temporal change in skewness for the studied species, we found a significant negative relationship between the time trend of skewness and the proportion of immatures in the catch. This would suggest that when the fishery exploits a higher percentage of the immature fraction of the population it would lead to a reduction of the relative proportion of juveniles (recruits) in the stock. Additionally, we found a positive relationship between the rates of change in abundance with the trend of the skewness along the time series, implying that when abundance increases this would be the result of an increase in recruitment. Taken together, both relationships would indicate that if the fishery tends to catch individuals below size at maturity, the reproductive capacity of the population would be limited, and productivity (i.e. production of recruits) would be lower, thus, reducing stock size. Although most of the species showed no significant trends in stock status along the last two decades, skewness could inform about ongoing changes in stock structure with potential implications on the recent fate of the population and future trajectories. Other authors have highlighted the importance of skewness to study population dynamics, for instance, negatively skewed colony size of coral populations were suggested to be related with degraded reef implying less recruitment and reduced replenishment (Rolf and Erik, 1998); and Ohlberger et al. (2013) related lake eutrophication and warming to a decrease in skewness in European perch. Furthermore, a decrease in skewness has been suggested as an early warning signal of anthropogenic disturbance in life organisms (De Soyza et al., 1997; Orfanidis et al., 2010). Therefore, our results are in line with those cited previously that point out paying attention to negatively skewed distributions and its implications for the good status of a population along time.

5. Conclusions

Artisanal fisheries are typically poor in data hindering effective fisheries management. On-board monitoring programmes offer certain advantages over scientific surveys, commonly unaffordable for a SSF. In this context, the analyses of body size indicators based on a large number of individuals of multiple species over a considerable number of years and along a wide geographical extent help to evaluate the status of fishery resources and make valid ecological and management inferences. For the Galician SSF, we can conclude that size-based indicators, in combination with abundance indices, suggest a stable performance of highly important species over the last two decades with few species showing signs of deleterious trends that deserve special attention. Our models also detected a generalized ontogenic deepening, strong seasonality, and negative density-dependent effect on body size. Finally, the analysis of the skewness of size frequency distributions suggests that exploiting a large proportion of individuals below size at maturity may have consequences with potential implications for stock productivity, and highlights the need of matching the establishment of simple management measures such as the MLS with basic reproductive reference points. However, in a multispecies and multigear context such as the Galician SSFs, the efficiency of the MLS would depend also on the fishing regime, implying that the application of any technical measure would be appropriate for some species but inadequate for others, thus, establishing priority targets would be required.

CRediT authorship contribution statement

Alexandre Alonso-Fernández: Conceptualization, Formal analysis, Visualization, Writing - original draft, Writing - review & editing. **Jaime Otero:** Conceptualization, Formal analysis, Writing - review & editing. **Rafael Bañón:** Data curation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement

The data underlying this article were provided by the *Unidade Técnica de Pesca Bajura* (UTPB) of *Conselleria do Mar* (CM) of the *Xunta de Galicia* (Regional Government of Galicia) by permission. Data will be shared on request to the corresponding author with permission of CM of the Xunta de Galicia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.107141.

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